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UNITED STATES PATENT APPLICATION

FOR

INTERCONNECTION ALLOY FOR INTEGRATED CIRCUITS

Inventor(s):

Donald S. Gardner
Thomas N. Marieb

Prepared By:

BLAKELY, SOKOLOFF, TAYLOR & ZAFMAN
12400 Wilshire Blvd., 7th Floor
Los Angeles, California 90025-1026
(310) 207-3800

BACKGROUND OF THE INVENTION

Field of the Invention

The invention relates generally to integrated circuits and more particularly to interconnecting individual devices of an integrated circuit.

Background Information

One direction in improving integrated circuit technology is to reduce the size of the components or devices on the integrated circuit chip, permitting an increased number of devices on the chip. The reduction in size of the devices of an integrated circuit chip requires reductions in the widths and thicknesses of the interconnections that connect the devices on the chip.

In general, the primary concerns of interconnection material is the material's longevity and its resistivity. Typically, modern interconnections are made principally of aluminum or an aluminum alloy, such as an aluminum-copper (Al-Cu) alloy or aluminum-silicon (Al-Si) alloy.

In general, grain boundaries are formed by the aluminum crystals that make up the aluminum or aluminum alloy interconnection. At present, the "micron" width and the "angstrom" thickness of a typical interconnection has become so

small that interactions between the current flowing through the interconnection and the grain boundaries between the aluminum crystals increasingly determine the limits in performance, reliability, and power consumption.

Where three grain boundaries meet, a triple point junction is formed. Such junctions are randomly dispersed throughout the interconnection and extend in a variety of directions that define potential inlet and outlet routes for displaced aluminum atoms during current flow. As electrical current flows through the interconnection, aluminum atoms are displaced the electrons. These displaced aluminum atoms accumulate in the grain boundaries that are downstream of the current and travel along the grain boundaries in the general direction of the current. At grain boundary junctions that have fewer upstream inlets than downstream outlets, a void may develop at that grain boundary junction in the interconnection over time as aluminum atoms erode from the junction.

FIG. 1 schematically illustrates an aluminum alloy interconnection and shows a number of junctions created by adjacent aluminum crystals. Interconnection **70** is formed, in this example, by a portion of aluminum crystal **72**, a portion of aluminum crystal **74**, a portion of aluminum crystal **76**, a portion of aluminum crystal **78**, and a portion of aluminum crystal **80**.

Grain boundary junction **82** is formed by the meeting of inlet grain boundary **84**, outlet grain boundary **86**, and outlet grain boundary **88**, the designation of inlet and outlet being dictated by the indicated direction of the flow of electrons. With one upstream inlet and two downstream outlets, more aluminum atoms can be expected to leave junction **82** through the two downstream outlets **86** and **88** than are supplied into junction **82** through the one upstream inlet **82**. With more aluminum atoms being removed from junction **82** within interconnection **70** than are being supplied to junction **82** from its upstream source, here inlet grain boundary **84**, void **90** eventually will develop in interconnection **70** at junction **82**.

The movement of aluminum atoms within an aluminum interconnection is known as electromigration and the time it takes for a void to develop into an open circuit in the interconnection may be described as the electromigration lifetime. One way to increase performance, reliability, and power consumption of integrated circuit interconnections is by improving the electromigration lifetime.

Several techniques have been developed to improve the electromigration lifetime of an interconnection. These techniques include improved texture, interlayers to limit void size, and interconnections of multiple layers of material such as a pure

aluminum layer as well as different layers formed from aluminum alloys.

A second concern of interconnections is resistivity. U.S. Patent No. 4,673,623, demonstrated that an alloy of aluminum, silicon, and titanium (Al-Si-Ti) provides hillock-free, dry-etchable, low resistivity electromigration resistant interconnections. Prior to the Al-Si-Ti alloy, interconnections of both aluminum-silicon (Al-Si) and aluminum-silicon-copper (Al-Si-Cu) were utilized. Although adding copper to aluminum-silicon improved the performance of the interconnection, the replacement of copper with titanium dramatically improved the performance of the interconnection by reducing the resistivity over an Al-Si-Cu interconnection.

What is needed is an electrical interconnection and an interconnection system with improved performance and reliability.

SUMMARY OF THE INVENTION

An interconnection of an aluminum-copper-Group IVA metal alloy is disclosed.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic illustration of the grain boundaries of aluminum crystals in an aluminum alloy interconnection.

FIG. 2 is a cross-section schematic of a titanium (Ti) underlayer on an interlayer dielectric in accordance with an embodiment of an interconnection stack of the invention.

FIG. 3 is the interconnection stack of **FIG. 2** after the further processing step of patterning an Al-0.5%Cu alloy in accordance with an embodiment of the invention.

FIG. 4 is the interconnection stack of **FIG. 2** after the further processing step of patterning a titanium-nitride (TiN) interlayer in accordance with an embodiment of the invention.

FIG. 5 is the interconnection stack of **FIG. 2** after the further processing step of patterning an Al-0.5%Cu alloy in accordance with an embodiment of the invention.

FIG. 6 is the interconnection stack of **FIG. 2** after the further processing step of patterning of a Al-0.5%Cu-0.1%Ti alloy in accordance with an embodiment of the invention.

FIG. 7 is a graphical comparison of the electromigration lifetime for various interconnections.

DETAILED DESCRIPTION OF THE INVENTION

The invention discloses an interconnection formed, for example, on a substrate of an integrated circuit chip where the material used to form the interconnection includes an aluminum-copper-Group IVA metal alloy. A Group IVA metal is a designation according to the International Union of Pure and Applied Chemistry (IUPAC) of elements having similar properties corresponding to their atomic structure. The interconnection and interconnection system as described herein has an increased electromigration lifetime by at least a factor of two with minimal impact on resistivity when compared to prior art interconnections.

A common method of utilizing interconnections in integrated circuits includes, but is not limited to, as part of a multilayer interconnection structure or interconnection stack. Examples include placing the primary interconnection material, such as for example an aluminum alloy, between titanium and/or titanium nitride (TiN) or between tantalum (Ta) and/or tantalum nitride (TaN). The titanium or tantalum materials act, in one sense, as diffusion barriers between the primary interconnection material and other layers above or below the primary interconnection material.

Reference is made to **FIGS. 2** to **6** to illustrate an interconnection stack and its manufacturing steps according to one

embodiment of the invention. The interconnection stack will connect, for example, individual devices on a chip or signals to or from the chip. A typical chip might have interconnection stacks made up of five or more layers, each interconnection stack separated from other interconnection stacks by interlayer dielectric (ILD) material. **FIGS. 2** to **6** describe the formation of an interconnection stack according to an embodiment of the invention over ILD on a semiconductor substrate, such as, for example, a silicon substrate having a plurality of devices formed in and on the substrate. The interconnection stack described is a Ti/TiN/Al-Cu-Group IV metal/Ti/TiN stack.

FIG. 2 shows the substrate after the processing step of patterning titanium (Ti) layer **110** over ILD layer **100**. To form an interconnection stack having a thickness of, for example, 4500Å to 5000Å, titanium layer **110** is deposited to a thickness of, for example, 400Å by use of DC magnetron sputtering in an atmosphere of argon at a total pressure of 5 mTorr, with a deposition rate of approximately 20 Å/second.

Titanium-nitride layer **115** is then deposited using, for example, an atmosphere of argon and nitrogen at a total pressure of 5 mTorr for 10 seconds to form overlying titanium-nitride layer **115** having a thickness of about 200 Å as shown in **FIG. 3.**

FIG. 4 shows the interconnection stack after the further processing step of depositing an aluminum-copper-Group IV metal layer **120** on the surface of titanium-nitride layer **115**. In one embodiment, the Group IV metal is titanium so that metal layer **120** is an aluminum-copper-titanium (Al-Cu-Ti) alloy. One embodiment of this alloy is a Al-0.5%Cu-0.1%Ti alloy. The percentages are atomic percentages of the individual atoms. Other atomic percentages of titanium, preferably less than the maximum solid solubility titanium in the alloy, may be used. Further, various atomic percentages of copper may also be used relative to its solid solubility and the desired resistivity properties of the interconnection. Al-Cu-Ti metal layer **120** is deposited in this embodiment, to a thickness of, for example, approximately 4100 Å using DC magnetron sputtering in an atmosphere of argon under conditions of a total pressure of 5 mTorr, and a deposition rate of 250 Å/second.

FIG. 5 shows the interconnection stack after the further processing step of depositing titanium layer **125** over metal layer **120**. In one embodiment, titanium layer **125** is deposited to a thickness of about 150 Å in a manner similar to that described above with reference to titanium layer 110. **FIG. 6** shows the interconnection stack after the further processing step of depositing titanium-nitride layer **130** to a thickness of, in one

embodiment, approximately 100 Å, in a manner similar to that described above with reference to titanium-nitride layer 115 on the surface of the interconnection stack to form an about 100 Å thick titanium-nitride layer **130**.

An embodiment of the interconnection stack of the invention as described above was evaluated against four other interconnections. The samples were tested at 225 °C in an electromigration testing device. To determine electromigration, the test applied a current density of 2.5 milliamps per centimeter squared (MA/cm^{2}) to a thirty percent rise in resistance on an interconnection formed of single level structures having a length of 1,000 microns and a width of 0.75 microns with the particular interconnection thickness indicated in angstroms (Å). Single level structures were used to omit blocking boundaries since blocking boundaries, formed, for example, when vias are used with tungsten, block the flow of aluminum atoms. Seven lines of each sample were tested and the tests were stopped after 4,000 hours.

Table I indicates the numeric results of testing the five samples as well as a description of each multilayer structure sample.

SAMPLE	MTTF	95% LCL	95% UCL	DESCRIPTION
1	400	295	542	1000Å TaAl/4400Å Al/150Å Ti/100Å TiN
2	634	478	341	150Å Ti/4400Å Al-0.5%Cu/150Å Ti/100Å TiN
3	708	638	786	400Å Ti/200Å TiN/2000Å Al-0.5%Cu/200Å TiN/2000Å Al-0.5%Å Ti/100Å TiN
4	1132	927	1383	400Å Ti/200Å TiN/5500Å Al-0.5%Cu/150Å Ti/100Å TiN
5	2527	1943	8286	400Å Ti/200Å TiN/4100Å Al-0.5%Cu-0.1% Ti/150Å Ti/100Å TiN

TABLE I

Sample 1 was a multilayer interconnection structure (or stack) comprised of an amorphous 1000 Å Ta-Al underlayer, a 4400 Å layer of aluminum overlying the Ta-Al underlayer with 150 Å of titanium overlaying the aluminum layer and a 100 Å titanium-nitride (TiN) layer overlaying the titanium layer.

Sample 2 was a multilayer interconnection structure formed by depositing 4400 Å of Al-0.5%Cu onto 150 Å of titanium and overlaying the Al-0.5%Cu with 150 Å of titanium, which itself was overlain by a 100 Å TiN layer.

Sample 3 was a multilayer interconnection structure essentially formed by dividing the Al-Cu layer of Sample 2 with a TiN layer. Sample 3 was formed by depositing 2000 Å of Al-0.5%Cu onto 200 Å TiN which itself was deposited onto 400 Å of titanium. The Al-0.5%Cu was overlain with 200 Å TiN which itself was

overlain by a 150 Å of titanium. This 150 Å of titanium was then overlain by a 100 Å TiN layer.

Sample 4 was a multilayer interconnection structure formed, as described above with reference to Figures 2-6 and the accompanying text, by depositing 200 Å of TiN onto a 400 Å titanium layer. Overlaying the TiN layer was 5500 Å of Al-0.5%Cu. Overlaying the Al-Cu layer was 150 Å of titanium, which itself was overlain by a 100 Å TiN layer.

Sample 5 was a multilayer interconnection structure of an embodiment of the invention formed by depositing 4100 Å of Al-0.5%Cu-0.1%Ti onto 200 Å of TiN overlaying a 400 Å titanium layer. Overlaying the Al-Cu-Ti layer of Sample 5 was 150 Å of titanium, which itself was overlain by a 100 Å TiN layer.

The results of the evaluation of the interconnection stack of the invention and the four other interconnections are summarized in **FIG. 7** and Table I. **FIG. 7** is a graph that shows the electromigration lifetime for each of the five samples tested. Indexed to the vertical axis of the graph in **FIG. 7** are error bars that span the 95% Lower Confidence Limit (LCL) to the 95% Upper Confidence Limit (UCL) and indicates the Mean Time To Failure (MTTF) in test run time hours.

As can be seen in **FIG. 7**, the most striking result was the electromigration lifetime of the sample of the embodiment of the

invention (Sample 5). One might expect that the addition of copper and titanium to aluminum possibly might achieve additive electromigration results (for example, increase in electromigration lifetimes proportional to the concentrations) given the known properties of Al-Ti and Al-Cu. However, as can be seen from Table I and **FIG. 7**, the results were multiplicative such that the electromigration lifetime for an aluminum alloy interconnection according to the invention was increased by at least a factor of two. Even more dramatic, the increase in lifetime by a factor of two underestimates the true MTTF since three of the seven Al-0.5%Cu-0.1%Ti alloy lines tested were still running at the time the tests were stopped, here 4000 hours.

One reason for the electromigration lifetime success of the interconnection of the invention may be that the amount of titanium added to the Al-0.5%Cu alloy keeps the copper in the Al-0.5%Cu-0.1%Ti alloy from diffusing into the surrounding layers. Titanium reacts with aluminum to form $TiAl_3$. With copper present, the titanium will react with the aluminum to form the complex $Ti(Al, Cu)_3$. Thus, from the standard interconnection alloy of Al-0.5%Cu, the addition of titanium allows approximately 0.2% of the 0.5%Cu to be maintained within the aluminum-copper-titanium alloy as $Ti(Al,Cu)_3$.

It is generally known that acceptable resistivity can be maintained in aluminum alloys by selecting an additive with a low maximum solid solubility. A low solid solubility (for example, on the order of less than one percent) tends to keep the lattice of the aluminum matrix from being distorted. Instead, precipitates tend to form or the solute segregates at the grain boundaries. It has been found that precipitates do not have a detrimental effect on the resistivity and can potentially improve the electromigration lifetime as well as the stress-induced voiding lifetimes.

It is known that the maximum solid solubility of titanium in pure aluminum is 0.57 % and the residual resistivity is about 2.9 μΩ-cm per 0.5 % titanium, depending upon the desired characteristics of the stacking material. In one embodiment, the amount of titanium present in the interconnection of the invention is 0.57 at.% or less.

Resistivity and transmission electron microscope (TEM) measurements of the Al-0.5%Cu-0.1%Ti alloy layer (from the multilayer interconnection structure described above) were evaluated. When taking into account the 0.81 μΩ-cm/at.% residual resistivity of copper in aluminum, one could expect that the maximum solid solubility of titanium in pure aluminum would result in a higher resistivity than observed in the Al-Cu-Ti alloys. In

this case, the resistivity would be about 3.5 μΩ-cm. Measurements of the resistivity of Al-0.5%Cu-0.1%Ti, however, were found to be similar to Al-0.5%Cu with values of 2.8 to 3.1 μΩ-cm.

TEM measurements of the interconnection of the invention were conducted to evaluate the physical properties of the alloy layer. Viewing the sample through a TEM showed no discernible difference in precipitate distribution between the Al-0.5%Cu-0.1%Ti alloy sample of the invention and a Al-0.5%Cu sample. Thus, the addition of 0.1% titanium to the traditional Al-0.5%Cu unexpectedly increases the lifetime of the interconnection by a factor of at least two while maintaining the resistivity and the texture of the interconnection.

A specific embodiment of the interconnection comprising an aluminum-copper-titanium alloy layer according to the invention has been described for the purpose of illustrating the manner in which the invention may be made and used. It should be understood that implementation of other variations and modifications of the invention and its various aspects will be apparent to those skilled in the art, who may develop a variation of structural details without departing from the principles of the invention. For example, the similarity between titanium and the other Group IVA metals or other metals such as tantalum similarly make such metals adequate to alloy with aluminum-copper to increase the

electromigration lifetime of an interconnection in a similar fashion. Further, the combination of the Al-Cu-Group IVA alloy in an interconnection stack need not be limited to a Ti/TiN stack, but may be employed with various other stack materials depending upon the desired characteristics of the stacking materials.